# Reproducibility of the quantum Hall effect

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Reporting on a comparison of four GaAs/AlGaAs-based quantum resistance standards mounted in a Wheastone bridge, this work shows that the quantum Hall resistance at Landau level filling factor $\nu = 2$ can be reproducible with a relative uncertainty of $32 \times 10^{-12}$ in the dissipation-less limit of the quantum Hall effect regime. In presence of dissipation, for example caused by the measurement current flowing, the discrepancy $\Delta R_{\mathrm{H}}$ measured on the plateau between quantum Hall resistors follows the so-called resistivity rule $B \times d(\Delta R_{\mathrm{H}})/dB \propto \overline{R_{xx}}$ where $\overline{R_{xx}}$ is the mean macroscopic longitudinal resistivity.

The quantum Hall effect (QHE)[1], which manifests itself by the Hall resistance quantization in two-dimensional electron gas (2DEG) at $R_{\mathrm{K}}/i$ values in the non-dissipative transport limit ($i$ is an integer and $R_{\mathrm{K}}$ is the von Klitzing constant equal to $h/e^2$ in theory[2], with $e$ the electron charge and $h$ is the Planck constant), has revolutionized the resistance metrology[3]: the ohm can be maintained with a relative uncertainty of $1 \times 10^{-9}$. This breakthrough also resulted from the advent of resistance bridges based on cryogenic current comparator (CCC)[4] using superconducting quantum interference devices (SQUID). The impact of the QHE in metrology was more recently enlarged by its implementation in the alternating current regime[5] and by the development of quantized Hall resistances (QHR) arrays[6]. A similar breakthrough occurred in the field of voltage unit following the discovery of the Josephson effect (JE)[7]. The major asset of the ohm representation by the QHE is its excellent reproducibility resulting from its link to the fundamental constants of physics. Practically, quantum standards must be independent of experimental implementation, material nature and sample properties provided that practical quantization criteria are fulfilled[8]. It remains a continuous challenge to check this reproducibility property both theoretically and experimentally. Thereby, a very small magnetic field dependent quantum electrodynamics correction to $R_{\mathrm{K}}$ was recently predicted[9]. Although its measurement is far beyond the present time capability, any new experimental test of the reproducibility property performed with a better accuracy will reinforce our confidence in the solid state quantum theory as a conerstone of the future *Système International* of units based on the fixing of fundamental constants of physics[10]. A major stake is the redefinition of the kilogram in terms of $h$ by means of the QHE and JE in the watt balance experiment[11]. Any lack of reproducibility of the QHE will further question the relation $R_{\mathrm{K}} = h/e^2$ and impact the *SI* redefinition. The most severe reproducibility tests of the QHE have been performed by comparing QHR in different materials leading hence to the so-called universality tests. QHR realized in GaAs/AlGaAs 2DEG and Si-Mosfet based samples[12, 13] were found to agree with a relative uncertainty of $3 \times 10^{-10}$. More recently, graphene has offered the opportunity of new stringent tests[14]: the QHR on the $\nu = 2$ plateau in graphene monolayer[15, 16] (resp. $\nu = -4$ plateau in graphene bilayer[17]) was recently found in agreement with the QHR in GaAs/AlGaAs within a relative uncertainty of $9 \times 10^{-11}$ (resp. $5 \times 10^{-7}$). Further reducing these uncertainties is timely to deepen the investigation of the relativistic QHE in graphene. The presently addressed comparison between the Integer

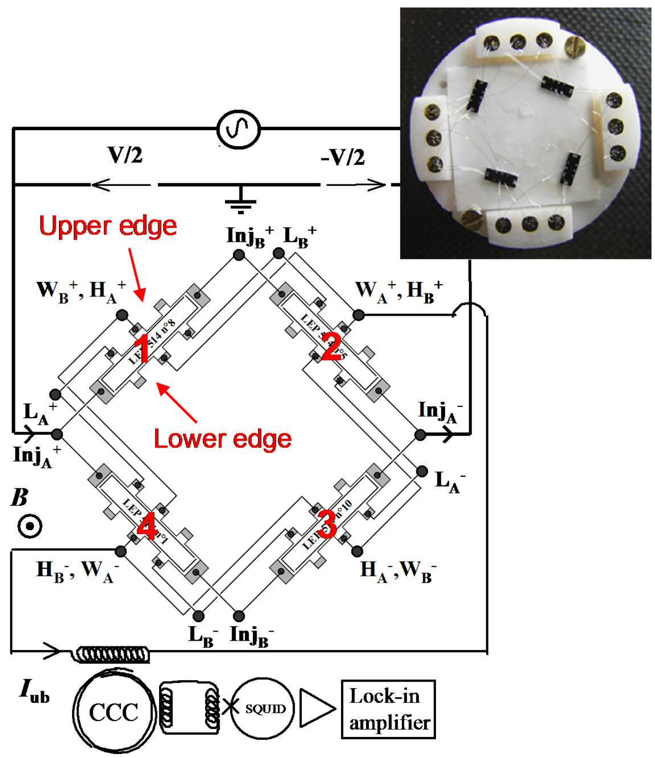


FIG. 1. Drawing of the experimental setup including the quantum Hall Wheatstone bridge made of four Hall bar samples (photography) and the CCC measuring the unbalance current.

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and Fractional QHE is another way to test the universality property[18]. More precise reproducibility tests can be performed by comparing quantum standards made of the same material and varying other experimental implementation conditions.

In this paper, we report on a comparison, performed using the original quantum Wheatstone bridge technique[19], of four different QHR, each made of the same GaAs/AlGaAs 2DEG widely used in metrology institutes[20]. A relative deviation of $-1.9 \times 10^{-12}$ covered by a record measurement relative uncertainty of $32 \times 10^{-12}$ $(1\sigma)$ is found between the QHR in the limit of dissipation-less state. The discrepancy between QHRs is measured as a function of magnetic field and of dissipation in the 2DEG. This new demonstration of reproducibility has a relative uncertainty three order lower than that of the $R_{\mathrm{K}}$ determination in the *SI* using the Thompson-Lampard capacitor[21]. It brings deepen knowledge for improving the practical realization of the resistance unit.

Fig.1 shows the Wheatstone bridge device made of four 400 $\mu$m-wide Hall bars connected by aluminum bonding wires using the triple connection technique based on fundamental properties of the QHE[22]. Each Hall bar has been individually checked according to the technical guidelines for the QHE metrological use[8]. All metallic contacts having a resistance lower than 0.1 $\Omega$, the resistance comparison error due to interconnections is strongly reduced by the multiple connection technique to a negligible level of $\sim 10^{-15}$. Fig. 1 presents the drawing of the Wheatstone bridge integrated into the experimental setup. The resistance unbalance of the bridge has been measured using the supplying terminal-pair $(Inj_A^+, Inj_A^-)$ and current detection terminal-pairs $(W_A^+,\ W_A^-)$ in configuration $\mathrm{C_A}$ and the terminal-pairs $(Inj_B^+, Inj_B^-)$ and $(W_B^+, W_B^-)$ in configuration $\mathrm{C_B}$ . In the Direct Current (DC) limit the relative unbalance current $I_{ub}/I$ of the Wheatstone bridge, where $I$ is the current circulating in each Hall bar, is related to the relative deviations $\alpha_j$ of each QHR $j$ to $R_{\mathrm{K}}/2$ : $[I_{ub}/I]_{CA} = -[I_{ub}/I]_{CB} = [(\alpha_2 + \alpha_4) - (\alpha_1 + \alpha_3)]/2$. It can be interpreted as the relative deviation of one particular quantum resistor among the others: $\Delta R/R = 2[I_{ub}/I]_{CA} = -2[I_{ub}/I]_{CB}$. In our experiment, the Wheatstone bridge is biased by a low frequency $f$ alternating voltage (between 0.10 Hz and 20 Hz) and the unbalance current $I_{ub}(f)$ is detected by a 3436 turns winding of a CCC used as amplifier. The 13.6 $\mu$A.turns/$\phi_0$ sensitivity of the CCC equipped with a $10^{-4}$ $\phi_0/\mathrm{Hz}^{1/2}$ white noise radio-frequency SQUID results in a 400 fA/Hz$^{1/2}$ current resolution. The polarization of the bridge and the signal detection at the output of the SQUID electronics are ensured by a Signal Recovery 7265 lock-in detector. At each measurement frequency, the angular phase of the lock-in detector is adjusted with a standard uncertainty of 20 $\mu$rad so that placing a 1 M$\Omega$ resistor parallel to one arm of the bridge, which produces a real impedance (resistance) unbalance, results in a signal only on the in-phase lock-in axis. Afterwards, the in-phase signal at frequency $f$ can be converted to an equivalent resistance unbalance $(\Delta R/R)_f$ that includes the QHR unbalance and others very small residual frequency dependent contributions caused by the measurement chain. The measurement procedure then consists in determining precisely the frequency dependence of $(\Delta R/R)_f$ to obtain $\Delta R/R$ alone by extrapolation to zero frequency. Each cable connected to the bridge is PTFE insulated and protected by a shielding at ground potential. Thus, only current leakage to ground can affect the comparison accuracy. But the symmetric polarization of the bridge sets current detection terminals at potential very close to ground: in-phase (out-phase) voltage is no more than $10^{-5}$ $(10^{-4})$ times $R_{\mathrm{H}}I$. It results that the measurement error of $\Delta R/R$ caused by current leakage is strongly reduced to about $10^{-5} \times R_{\mathrm{H}}/R_{\mathrm{G}}$, where $R_{\mathrm{G}} \gg 10^{12}$ $\Omega$ is the insulation resistance between cable inner and ground. The measurement uncertainty of $\Delta R/R$ therefore boils down to the statistical measurement uncertainty as reported in all figures.

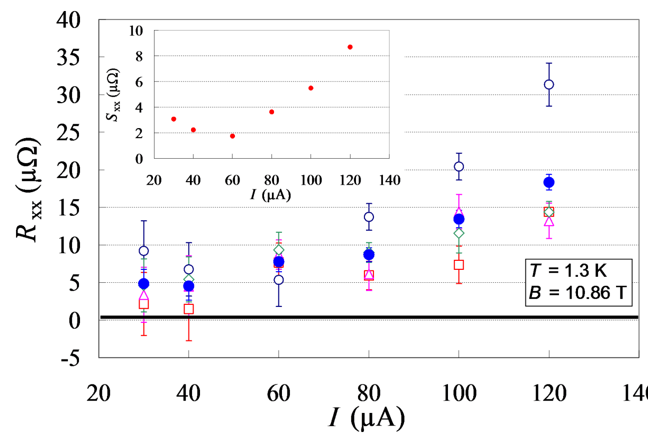


FIG. 2. Current dependence of $R_{xx}(A^+)$ (open blue circle), $R_{xx}(A^-)$ (open red square), $R_{xx}(B^+)$ (open magenta triangle) , $R_{xx}(B^-)$ (open green diamond), mean value $\overline{R_{xx}}$ (filled blue circle). Inset: standard deviation $S_{xx}$.

The perfect quantization state of the QHE is only reached in the zero dissipation limit. The longitudinal resistivity which is assumed to measure the dissipation level cannot be determined independently in each quantum resistance standard once the Wheatstone bridge is mounted. But, using $H_A^+, H_A^-, L_A^+, L_A^-$ voltage terminals, four resistance which are different combination of two longitudinal resistivity $r_{xx}$ of individual Hall bars can be measured using a EMN11 nanovoltmeter with an accuracy around 1 $\mu\Omega$: $R_{xx}(A^+) = (W/L)|H_A^+ - L_A^+|/I = (r_{xx}^{Up}1 + r_{xx}^{Up}4)/2$, $R_{xx}(A^-) = (W/L)|H_A^- - L_A^-|/I = (r_{xx}^{Lo}2 + r_{xx}^{Lo}3)/2$, $R_{xx}(B^+) = (W/L)|H_B^+ - L_B^+|/I = (r_{xx}^{Up}2 + r_{xx}^{Lo}1)/2$, $R_{xx}(B^-) = (W/L)|H_B^- - H_B^-|/I = (r_{xx}^{Lo}4 + r_{xx}^{Up}3)/2$ (Up and Lo exponents which complete the $r_{xx}$ notation refers to upper and lower edges respectively). Fig. 2 shows that the current behaviors of these

four $R_{xx}$ quantities, measured at the center of the $\nu = 2$ plateau ($B$=10.86 T), are similar in the current range investigated. The current behavior of their mean value $\overline{R_{xx}}$, equal to the mean value $\overline{r_{xx}}$, seems therefore very representative of the behavior with current in each Hall bar. In addition, $R_{xx}(A^+)$ discards much more from the mean value $\overline{R_{xx}}$. This is in agreement with the conclusion drawn from individual characterizations showing that $r_{xx}^{Up}$ was higher in the Hall bar sample numbered 1. Although the resistances $R_{xx}(A^+)$, $R_{xx}(A^-)$, $R_{xx}(B^+)$ and $R_{xx}(B^-)$ are correlated because $r_{xx}^{Up}j$ and $r_{xx}^{Lo}j$ characterize the same sample $j$, the standard deviation $S_{xx} = (1/\sqrt{3})[(R_{xx}(A^+) - \overline{R_{xx}})^2 + (R_{xx}(A^-) - \overline{R_{xx}})^2 + (R_{xx}(B^+) - \overline{R_{xx}})^2 + (R_{xx}(B^-) - \overline{R_{xx}})^2]^{1/2}$ is a useful quantity reflecting the $r_{xx}$ dispersion among Hall bars. Its dependence on current is similar to that of $\overline{R_{xx}}$ (see inset of fig.2).

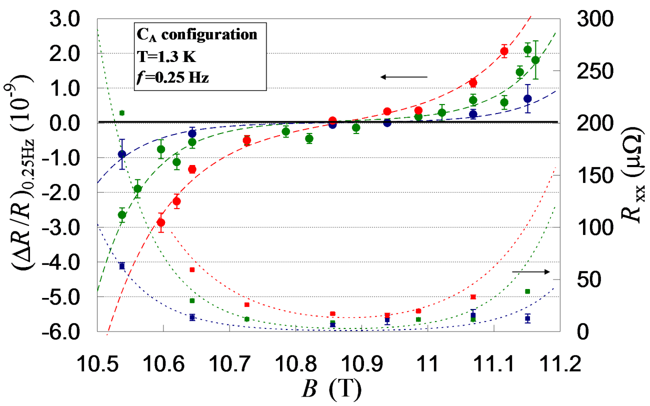


FIG. 3. $(\Delta R/R)_{0.25Hz}$ and $\overline{R_{xx}}$ as a function of the magnetic induction $B$ for 40 $\mu A$ (blue), 80 $\mu A$ (green) and 120 $\mu A$ (red) measurement currents. Dashed lines are interpolation curves of $(\Delta R/R)_{0.25Hz}$. Dotted lines are representations of $2.7 \times 10^{-2} \times B \times (d(\Delta R)/dB)_{0.25Hz}$ functions.

Fig. 3 shows that the discrepancy $(\Delta R/R)_{0.25Hz}$, measured in configuration $C_A$ at $T = 1.3$ K, as a function of the magnetic induction $B$ forms a plateau with a finite slope increasing with current. All plateaus measured with different currents intercept zero discrepancy value at a common magnetic induction $B_P = 10.86$ T defining an apparently current independent fixed pivotal point within a $10^{-10}$ uncertainty. At $B_P$, $\overline{R_{xx}}$ is minimal and the Landau level filling factor $\nu = \overline{n_s}h/(eB_P)$, calculated using the mean value of the electron densities in the four Hall bars $\overline{n_s} = 5.19 \times 10^{11}$ cm$^{-2}$ is 1.98, therefore very close to 2. The observation of such a fixed point comes from the electron densities of the four Hall bars differing between them by less than $10^{-2}$ in relative value. $\overline{R_{xx}}$ at each current can be very well adjusted by the function $2.7 \times 10^{-2} \times B \times (d(\Delta R)/dB)_{0.25Hz}$ (see dotted lines in figure 3), with $(d(\Delta R)/dB)_{0.25Hz}$ the derivative of functions interpolating $(\Delta R/R)_{0.25Hz}$ curves. The linear relationship between the slope $(d(\Delta R)/dB)_{0.25Hz}$ and $\overline{R_{xx}}$ notably means that the plateau is perfectly flat in the dissipation-less limit, as expected. Similarly, it is found that $S_{xx} \sim 2.3 \times 10^{-2} \times B \times (d(\Delta R)/dB)_{0.25Hz}$ showing that the observation of $(\Delta R/R)_{0.25Hz}$ plateau tilting in our experiment probably results from the small difference existing between $r_{xx}$ values in the four Hall bars as yet concluded from fig. 2. The observation of a linear relationship between the Hall plateau slope and the longitudinal resistance, know as the resistivity rule (RR)[23–26], was reported in 2DEG by several groups. This is a very general relation which also applies to the thermopower tensor in the QHE regime[27]. It was proposed that this linear relationship results from large scale density fluctuations[28, 29]. In this model, the macroscopic dissipative resistivity $\overline{R_{xx}}$ depends only on the fluctuations of the microscopic transverse resistivity $\delta\rho_{xy}$ caused by the spatial variations of the filling factor and is no more linked to the microscopic resistivity $\rho_{xx}$ assumed to be $\ll \delta\rho_{xy}$. It results that $\overline{R_{xx}} \sim \alpha \times B \times dR_{xy}/dB$ where $\alpha$ is given by $C\delta n_s/n_s$ and $C$ is assumed to be order unity. The value of $\alpha = 2.7 \times 10^{-2}$ deduced from our adjustments is in agreement with the relative density fluctuations of $10^{-2}$ measured between samples. The observation of the (RR) on the $\nu = 2$ plateau at the $10^{-9}$ accuracy seems to indicate that the microscopic dissipation characterized by $\rho_{xx}$ is very low. In the scope of this model, $\overline{R_{xx}}$ would simply be an upper bound of $\rho_{xx}$, which turns out to be very low. However, the longitudinal resistance stays a relevant quantization criterion since directly linked to Hall resistance deviations. More practically, it appears that reproducing $R_K$ value within $10^{-10}$ requires samples with very low $r_{xx}$ value and highly carrier density as well as very precise determination of the magnetic field giving the minimum of $r_{xx}$.

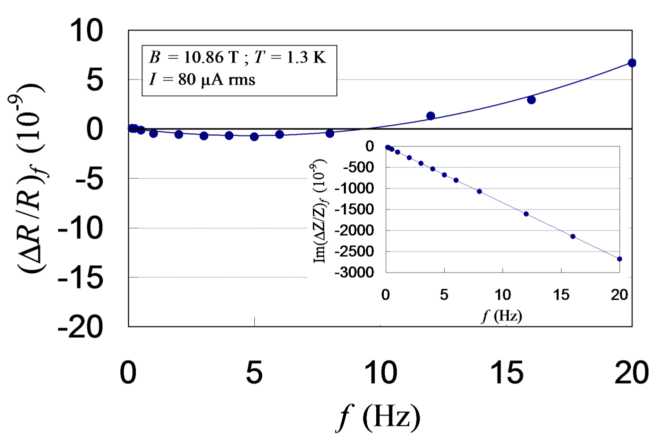


FIG. 4. Frequency dependence of $(\Delta R/R)_f$ $(Im(\Delta Z/Z)_f$ in inset) in measurement configuration $C_A$. Uncertainty bars are smaller than blue circle size.

At $B_P = 10.86$ T, the $\nu = 2$ plateau center which gives minimal discrepancy as well as minimal $\overline{R_{xx}}$ value, the frequency dependence of $(\Delta R/R)_f$ between 0.15 Hz and 20 Hz was accurately measured to determine $\Delta R/R$ by extrapolation to $f = 0$ Hz. These measurements were

TABLE I. Current dependence of mean longitudinal resistance and relative deviations to quantization.

| $I$ ($\mu A$) | $\overline{R_{xx}}$ ($\mu\Omega$) | $(\Delta R/R)_{\mathrm{C_A}}$ ($10^{-12}$) | $(\Delta R/R)_{\mathrm{C_B}}$ | $(\Delta R/R)_{\mathrm{C_{AB}}}$ |
|---|---|---|---|---|
| 40 | $6.2 \pm 1.6$ | $-3.9 \pm 48.7$ | $17.6 \pm 71.3$ | $2.9 \pm 40.2$ |
| 80 | $8.5 \pm 0.8$ | $68.4 \pm 20.6$ | $48.3 \pm 19.5$ | $57.8 \pm 14.2$ |
| 120 | $17.1 \pm 0.9$ | $119.4 \pm 19.3$ | $48.6 \pm 37.5$ | $104.5 \pm 17.2$ |

performed for current values of 40 $\mu$A, 80 $\mu$A and 120 $\mu$A using measurement configurations $\mathrm{C_A}$ and $\mathrm{C_B}$. Fig. 4 reports on $(\Delta R/R)_f$ ($Im(\Delta Z/Z)_f$ in inset) as a function of frequency $f$ for measurement configuration $\mathrm{C_A}$ and a current of 80 $\mu$A. Each determination at a given frequency is the weighted mean value of several measurements with acquisition time as long as 50 000 s. Allan variance analysis shows that the standard mean deviation is an adequate estimate of the uncertainty (noise is white, no $1/f$ noise is observable). $(\Delta R/R)_f$ can be perfectly adjusted by a second order polynomial function which is different for $\mathrm{C_A}$ or $\mathrm{C_B}$ measurement configurations. The understanding of the frequency dependence is beyond the scope of the paper. However, let us just remark that the linear frequency dependent term has a significant amplitude of $-3.07 \times 10^{-7}$/kHz in configuration $\mathrm{C_A}$ that could result from losses in capacitances as was observed at higher frequency (some kHz)[5].

The extrapolation of $(\Delta R/R)_f$ to $f = 0$ Hz measured in configurations $\mathrm{C_A}$ and $\mathrm{C_B}$ for each current results in $\Delta R/R_{\mathrm{C_A}}(I)$ and $\Delta R/R_{\mathrm{C_B}}(I)$ respectively, the weighted mean value $\Delta R/R_{\mathrm{C_{AB}}}(I)$ of which can then be calculated. All values are reported in Table 1. Inset of Fig.5 shows $\Delta R/R_{\mathrm{C_{AB}}}(I)$ as a function of current. $\Delta R/R_{\mathrm{C_{AB}}}(I)$ reported as a function of $\overline{R_{xx}}(I)$ (see fig. 5) exhibits a linear relationship with a coupling factor of 0.08. We then used a generalized $\chi$-two linear least square method to extrapolate $\Delta R/R_{\mathrm{C_{AB}}}$ to $\overline{R_{xx}} = 0$. The result is $\Delta R/R_{\mathrm{C_{AB}}}(\overline{R_{xx}} = 0) = (-1.9 \pm 31.8) \times 10^{-12}$. It demonstrates with a record relative uncertainty of $32 \times 10^{-12}$ the reproducibility of the quantized Hall resistance on the $\nu = 2$ plateau in the GaAs samples if they are in the dissipation-less state. For a minimal $\overline{R_{xx}}$ value higher than 20 $\mu\Omega$, the QHR departs from each others by more than $1 \times 10^{-10}$ at the center of the $\nu = 2$ plateau. $\Delta R/R_{\mathrm{C_{AB}}}(I)$ was also reported as a function of $S_{xx}(I)$ showing a linear relationship. The extrapolation to $S_{xx} = 0$ gives $\Delta R/R_{\mathrm{C_{AB}}}(S_{xx} = 0) = (12 \pm 29.9) \times 10^{-12}$. This result means that the discrepancy between quantum Hall resistances cancels if the four Hall bars have the same macroscopic longitudinal resistance. This claims for a similar mechanism linking the Hall and the longitudinal resistances in each Hall bar. This confirms the hypothesis previously evoked that the discrepancy observed at finite current probably results from unequal longitudinal resistance values in the four Hall bars.

Considering the magnetic field dependence of $(\Delta R/R)_{0.25Hz}$ expressed by the (RR)(see fig. 3), the linear behavior of $\Delta R/R$ as a function of $\overline{R_{xx}}$ can simply result either from the $\sim 10^{-2}$ T-inaccuracy of the magnetic induction experimental realization of the pivotal point or from its indetermination itself due to the $10^{-2}$-dispersion of the electron densities of the four Hall bars. The existence of small effective misalignments of QHR Hall probes, usually explained by the carrier density inhomogeneity[30] or the chiral nature of the current flow in finite width voltage terminals[31], can also explain the observed linear coupling. Although samples have very close geometry, the deviations caused by the finite width of voltage terminals should not totally compensate since longitudinal resistances are different in the four Hall bars.

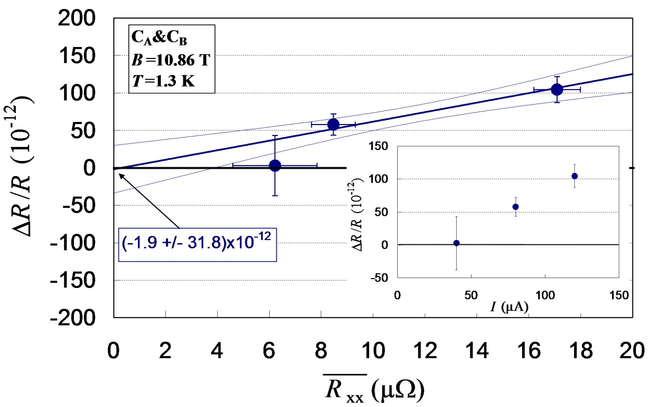


FIG. 5. Relative resistance deviation between quantum Hall resistances $\Delta R/R_{\mathrm{C_{AB}}}$ as a function of the mean longitudinal resistance $\overline{R_{xx}}$. Linear adjustment of $\Delta R/R_{\mathrm{C_{AB}}}(\overline{R_{xx}})$ (thick blue line) and $1\sigma$ standard deviations (thin blue line). Inset: $\Delta R/R_{\mathrm{C_{AB}}}$ as a function of current.

This work demonstrates the perfect reproducibility of the quantum Hall effect with a record accuracy of $32 \times 10^{-12}$. This is a new result supporting a revision towards a *Système International* of units taking into account quantum physics. It also shows how the Hall resistance on the $\nu = 2$ plateau in our GaAs samples departs from $R_{\mathrm{K}}/2$ as a function of minimal longitudinal resistivity. For instance, a longitudinal resistance higher than 20 $\mu\Omega$ leads to a relative discrepancy to quantization of the Hall resistance higher than $10^{-10}$. The accuracy of the reported comparison was limited by the sensitivity of the CCC. A current sensitivity of 20 fA/Hz$^{1/2}$ can be achieved using a 4000 turns detection winding of a DC SQUID based CCC[32] with a sensitivity of about 80 pA.turn/Hz$^{1/2}$. Comparisons of quantum resistance standards, for example made of GaAs and graphene[14], could therefore be performed with an accuracy $\sim 10^{-12}$ using the Wheatstone QHE bridge technique.

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[1] K. V. Klitzing, Phys. Rev. Lett. **45**, 494 (1980).
[2] D. Yoshioka, *The quantum Hall effect* (Springer, 1998).
[3] B. Jeckelmann and B. Jeanneret, Rep. Prog. Phys. **64**, 1603 (2001).
[4] I. K. Harvey, Rev. Sci. Instrum. **43**, 1626 (1972).
[5] F. J. Ahlers, B. Jeannneret, F. Overney, J. Schurr, and B. M. Wood, Metrologia **46**, R1 (2009).
[6] W. Poirier and F. Schopfer, Eur. Phys. J. Spec. Top. **172**, 207 (2009).
[7] B. Jeanneret and S. P. Benz, Eur. Phys. J. Spec. Top. **172**, 181 (2009).
[8] F. Delahaye and B. Jeckelmann, Metrologia **40**, 217 (2003).
[9] A. A. Penin, Phys. Rev. B. **79**, 113303 (2009), 81, 089902 (E) (2010).
[10] I. M. Mills, P. J. Mohr, T. J. Quinn, B. N. Taylor, and E. R. Williams, Metrologia **43**, 227 (2006).
[11] A. Eichenberger, G. Genevès, and P. Gournay, Eur. Phys. J. Spec. Top. **172**, 363 (2009).
[12] A. Hartland, K. Jones, J. M. Williams, B. L. Gallagher, and T. Galloway, Phys. Rev. Lett. **66**, 969 (1991).
[13] B. Jeckelmann, B. Jeanneret, and D. Inglis, Phys. Rev. B **55**, 13124 (1997).
[14] W. Poirier and F. Schopfer, Nature Nanotechnology **5**, 171 (2010).
[15] A. Tzalenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolillo, M. S. Syvajarvi, R. Yakimova, O. Kazakova, T. J. B. M. Janssen, V. Falko, and S. Kubatkin, Nature Nanotechnology **5**, 186 (2010).
[16] T. J. B. M. Janssen, N. Fletcher, R. Goebel, J. Williams, A. Tzalenchuk, R. Yakimova, S. Kubatkin, S. Lara-Avila, and V. Falko, New J. Phys. **13**, 093026 (2011).
[17] J. Guignard, D. Leprat, D. C. Glattli, F. Schopfer, and W. Poirier, Phys. Rev. B **85**, 165420 (2012).
[18] F. J. Ahlers, E. Pesel, K. Pierz, P. Warnecke, and W. Wegscheider, in *2008 CPEM Digest*, Boulder, edited by A. H. Cookson and T.-L. Winter (IEEE Trans. Instrum., 2008) p. 16.
[19] F. Schopfer and W. Poirier, J. Appl. Phys. **102**, 054903 (2007).
[20] F. Piquemal, G. Genevès, F. Delahaye, J. P. André, J. N. Patillon, and P. Frijlink, IEEE Trans. Instrum. Meas. **42**, 264 (1993).
[21] W. Poirier, F. Schopfer, J. Guignard, O. Thevenot, and P. Gournay, CRAS **5**, 171 (2011).
[22] F. Delahaye, J. Appl. Phys. **73**, 7914 (1993).
[23] A. M. Chang and D. C. Tsui, Solid State Commun. **56**, 153 (1985).
[24] T. Rötger, G. J. C. L. Bruls, J. C. Maan, P. Wyder, K. Ploog, and G. Wiemann, Phys. Rev. Lett. **62**, 90 (1989).
[25] H. Stormer, K. Baldwin, L. N. Pfeiffer, and K. W. West, Solid State Commun. **84**, 95 (1992).
[26] W. Pan, J. S. Xia, H. L. Stormer, D. C. Tsui, C. L. Vicente, E. D. Adams, N. S. Sullivan, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **95**, 066808 (2005).
[27] B. Tieke, R. Fletcher, U. Zeitler, A. K. Geim, M. Henini, and J. C. Maan, Phys. Rev. Lett. **78**, 4621 (1997).
[28] S. H. Simon and B. I. Halperin, Phys. Rev. Lett. **73**, 3278 (1994).
[29] S. H. Simon and N. R. Cooper, Phys. Rev. B **56**, R7116 (1997).
[30] Dominguez, Ph.D. thesis, CNAM, Paris (1987).
[31] W. van der Wel, C. J. P. M. Harmans, and J. E. Mooij, J. Phys. C **21**, L171 (1988).
[32] L. Soukiassian, G. Spengler, D. Leprat, F. Schopfer, and W. Poirier, in *2010 CPEM Digest*, Daejeon, edited by Y. S. Song and J.-S. Kang (IEEE Trans. Instrum., 2010) p. 761.